Heat capacity of adsorbed Helium-3 at ultra-low temperatures

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We report on direct measurements of the heat capacity of monolayers of ^{3}He adsorbed on the surface of a cell filled with superfluid ^{3}He. We found that at ultra low temperatures the surface ^{3}He heat capacity dominates over the heat capacity of the bulk liquid ^{3}He. The replacement of adsorbed ^{3}He by ^{4}He changes the heat capacity of the sample by an order of magnitude. These investigations were made in the framework of the "ULTIMA" project, a dark matter detector based on superfluid ^{3}He in the limit of ultra low temperatures.

1. INTRODUCTION

A closed cell with a small orifice, immersed into superfluid ^{3}He at very low temperatures is a very versatile device; it can be used as a thermal source of quasiparticles (Black body radiator)[1] or as a very sensitive bolometer, if one measures the temperature inside the cell. The last approach can be used for detecting elementary particle events inside the cell[2,3].

The big advantage of this type of bolometers is the possibility to calibrate it by direct heating of the quasiparticles by a mechanical moving object. For the purpose of both, thermometry and heating, we have used Vibrating Wire Resonators (VWR). VWR thermometers at ultra low temperatures are well studied objects[4,5]. For the calibrated heat pulses we have used a second VWR present in the cell[6]. The direct calibration procedure makes this type of bolometers a very special particle detector, as it does not rely on a relative or "theoretical" calibration.

During our work on a dark matter detector prototype, we noticed that the calibration factor showed big differences depending on the method used to fill our cells with ^{3}He. If filled under cold conditions ($\approx$ 10 mK) the calibration factor, which is inversely proportional to the heat capacity, is

down to 15 times smaller than if filled under warm conditions ($\approx$ 2 K). We ascribe this difference to a difference of coverage of the walls of the cell; If filled under cold conditions, then the ^{3}He separates into a phase of pure ^{3}He and a few droplets of ^{4}He, the separation taking place in the guard cell and on the heat exchangers. The bolometrical cells are therefore filled up only by pure ^{3}He. Under warm conditions of ^{3}He condensation in the cell, the ^{4}He impurities penetrate down to the bolometric cell and cover the cell walls. 2 ppm concentration of ^{4}He in the bolometrical cell is sufficient to cover the whole cell by 2 monolayers of solid ^{4}He. At an earlier stage, we had already observed this effect qualitatively. Here we report a quantitative study of this phenomenon.

2. BOLOMETRIC CALIBRATION BY HEATER PULSES

The bolometrical cells are 0.13 cm^3 copper boxes filled with superfluid ^{3}He-B and linked to an outer ^{3}He-B reservoir by a small orifice. The temperature inside the cell is monitored by a Vibrating Wire Resonator (VWR) driven at its resonance frequency. After a heating event caused for example by a cosmic particle, the temperature inside the cell will suddenly rise, and then go back to its initial temperature by thermalisation via the hole. A method used to simulate such an event is to introduce by a second VWR a well known energy by mechanical friction[1,3]. For small enough pulses, the height of the resulting peak (H, in Hz) is proportional to the heat injected (E), and we can define the calibration coefficient as $\sigma = H/E$. A detailed calculation shows that this calibration coefficient is inversely proportional to the heat capacity (C) : $\sigma \propto 1/C$.

During our experiment we first filled very slowly the cell with ^{3}He when the cryostat already was at very low temperatures ($\approx$ 10 mK). The heater pulses done in the subsequent 7 demagnetisation runs all showed unusually low response on the thermometer wire and hence low calibration coefficients (see fig. 1). Between these runs, the temperature in the cell never went above 100 mK. After the seventh demagnetisation, we heated to about 10 K in order to evaporate all of the Helium and to force a redistribution of the adsorbed layers. After recooling to ultra low temperatures, the following pulses all showed much higher pulse responses.

In addition to the different peak heights a second difference characterises the effect. While the decline of the "large" peaks follow an exponential law, with the time constant τ_b determined by the size of the orifice and as predicted by simple kinetic theory, the decline of the "small" peaks show two different time constants, as if the quasiparticle excitations were in exchange

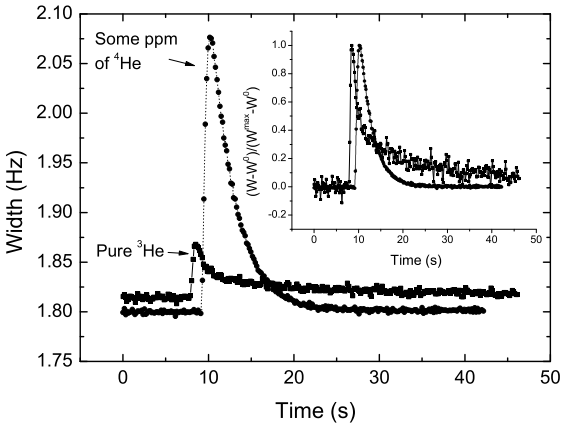

Fig. 1. Response peaks to a heater pulse of same energy (750keV) and at almost the same baseline width for the cell filled by Helium in cold and warm conditions. The insert shows the normalized peaks in comparison. A striking feature is the much slower thermalisation in the case of pure ^{3}He.

with an additional heat reservoir.

All these effects point to solid Helium, either -3 or -4, adsorbed on the walls of the cell. If it is ^{3}He, it corresponds to a huge heat capacity, well connected to the system of quasiparticles. In the case of ^{4}He coverage its heat capacity is negligibly small, the only (or at least dominating) heat capacity will be the heat capacity given by quasiparticle excitations of the bulk ^{3}He.

Before and after "rebaking" the adsorbed layers, a big effort has been made to measure the calibration coefficient at different temperatures (see fig. 2). For each of the points, at least 15 pulses of different energies have been made, and the calibration factor has been obtained by a linear fitting of the peak height/energy plot. In the plot, the two series of points can be clearly distinguished.

The calibration factor after rebaking shows only a weak dependence on temperature. It corresponds to the calibration factor :

$$\sigma_0 = \frac{\delta W}{\delta U} = \frac{1}{C}\frac{dW}{dT}$$

With $dW/dT \propto T^{-2}exp(-\Delta/k_bT)$ and $C_{bulk} \propto T^{-3/2}exp(-\Delta/k_bT)$ we get $\sigma_0 \propto T^{-1/2}$. The actually measured calibration factor is lower than this value mainly due to the finite response time of the VWR, an effect that gets bigger at lower temperatures. A more detailed analysis of the problem has been made and, considering all corrections, the plot can be fitted with only one adjustable parameter, a geometric factor characterising the wire.

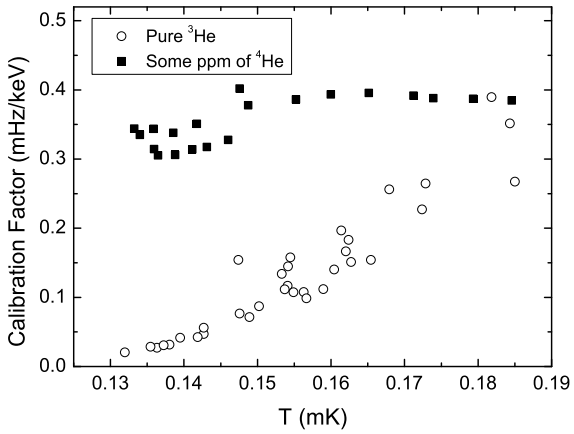

Fig. 2. Calibration factor for different temperatures before and after rebaking. The curve after rebaking only slightly depends on temperature, because the exponential dependence of both the quasiparticle density and the VWR line width cancel out. In the pure ^{3}He case, the surfaces give a non-exponential contribution to the heat capacity, resulting in a strong decline of the calibration coefficient.

The calibration coefficient before rebaking shows a much stronger temperature dependence. This can be explained when one considers an additional heat capacity which does not show an exponential dependence: $C = C_{bulk} + C_{surface}$. In this case, for low temperatures, the heat capacity will be dominated by the contribution of the surface, and the exponential term coming from dW/dT will not cancel out anymore.

3. SURFACE HEAT CAPACITY

From the fact that in fig. 1 we see two time constants for the decline of the lower pulse, we deduce that the thermalisation time between the bulk and the surface is of the same order of magnitude as the response time of the wire and the thermalisation time of the box. Hence, at the moment of the maximal height, these two systems are most probably not yet in thermal equilibrium, with the bulk being warmer than the surface. Nevertheless, a method to get an approximation, a lower estimation to be exact, consists in considering that both systems are in perfect contact. Under this assumption, the only influence of the surface is to increase the heat capacity of the total system. The characteristics of the thermometer wire being the same we thus

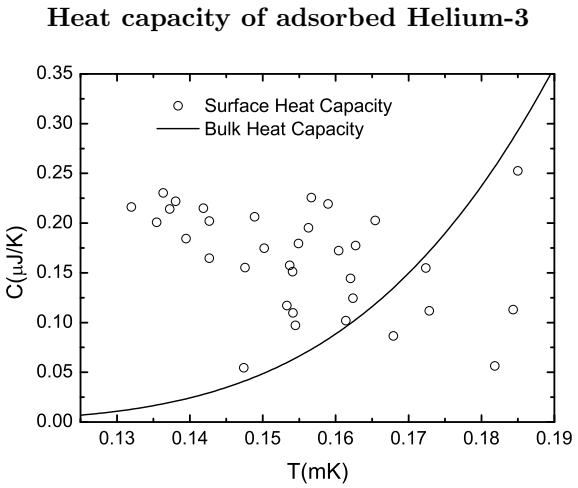

Fig. 3. Surface heat capacity as a function of temperature. The bulk heat capacity has been calculated using the BCS formula and the surface heat capacity is determined by the ratio of the calibration factors (see fig. 2) times the bulk heat capacity (eqn. 1).

get:

$$\frac{\sigma_{after}}{\sigma_{before}} = \frac{c_{bulk} + c_{surface}}{c_{bulk}} \tag{1}$$

As the formula for calculating the bulk heat capacity is well known, we can determine the surface heat capacity as shown in fig. 3.

Considering a surface of $1.5{*}10^{-4}\mathrm{m}^2$, calculated from the geometric dimensions of the cell, regardless of the rugosity of the copper walls, we find a surface heat capacity of approximately 1000 $\mu\mathrm{JK}^{-1}\mathrm{m}^{-2}$ at 150 μK, a value about 2 orders of magnitude higher than what has been found in the mK range (see ref. 7 and refs. therein). One main difference with previous experiments, apart from the different temperature range, is the presence of a magnetic field ranging from 60 mT to 150 mT. At our working temperatures of about 150μK we are thus in the vicinity of the maximum of the Schottky anomaly of the adsorbed ^{3}He. This leads us to believe that the addendum specific heat is of magnetic nature.

4. DISCUSSION

The error bars in fig. 2 and fig. 3 are of about the same size as the symbols. Thus, the quite big scattering should have a physical reason. One possibility is the influence of the magnetic field. For the calibrations done without the surface heat capacity, a clear dependency is observed that the calibration coefficient decreases with increasing field. Detailed measurements

on this effect are still running and could be linked to the magnetic dependence of the superfluid gap. For calibrations with addendum specific heat, the same tendency can be observed, but results are much less clear. In fact it seems that for each demagnetisation run, the observed calibration coefficient changes, and that thus the obtained parameters are not comparable. Additionally we want to point out that the temperature plotted on the x-axis is calculated from the VWR-Width measured, using a formula which is derived in the zero field limit[8]. Newer experiments seem to indicate that the influence of the magnetic field is not negligible[9] and that we should take into account some correction for the temperature axis.

To conclude with, we have demonstrated the difference between "hot" and "cold" filling up of a bolometrical cell, and measured the additional heat capacity related to adsorbed solid ^{3}He on the copper walls.

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